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Abstract

Dynamic envelope/lighting systems have the potential to optimize the perimeter zone energy balance between daylight admission and solar heat gain rejection on a real-time basis, and to increase occupant comfort. Two side-by-side full-scale offices in Oakland, California were built to further develop and test this concept. An automated venetian blind was operated in synchronization with a dimmable electric lighting system to block direct sun, provide the design workplane illuminance, and maximize view. The research program encompassed system design refinements, energy measurements, and human factors tests. In this study, we present lighting energy and cooling load data that were monitored in this facility over the course of a year.

Significant energy savings and peak demand reductions were attained with the automated venetian blind/ lighting system compared to a static venetian blind with the same dimmable electric lighting system. Correlations between key weather parameters and cooling and lighting were used to illustrate how the dynamic system was able to simultaneously achieve optimization between lighting and cooling end uses under the full range of weather conditions of this sunny, moderate climate. Energy-efficiency estimates were conservative since experience shows that conventional daylighting control systems and manually operated shading devices are rarely used effectively in real world applications.

1. Introduction

The category of "dynamic" window technologies encompasses numerous conventional components such as motorized louvers, venetian blinds, and shades, as well as more advanced glazing systems such as switchable electrochromics[1], thermochromics, polymer dispersed liquid crystal glazings, and electrically heated glazings. These building envelope technologies offer promising energy-efficiency opportunities and the potential to provide higher quality work environments. Substantial research has been devoted to passive heating applications, with dynamic window systems working as heat exchange systems. Computer simulations, laboratory tests, or reduced-scale field tests document the energy

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1 An electrochromic glazing is a thin multi-layer coating on glass that switches from a clear to a colored state with a small applied voltage.

benefits associated with this application; e.g. automated between-pane venetian blinds controlled by temperature and solar position [1].

For climates with high daylight availability and building types that are cooling load dominated, dynamic window technologies can be employed for a different purpose. Coupled with daylighting controls, window technologies that possess a broad range of daylight transmission and solar heat gain rejection properties can be used to actively optimize daylight, reduce electric lighting loads, and reduce the respective solar and lighting heat gains at perimeter zones of commercial buildings. Less research has been devoted to such systems. While there are dynamic shading *or* dimmable lighting systems commercially available today, there are no commercially-available, dynamic window systems that are designed to operate in synchronization with the lighting system. We have summarized simulation studies that have been conducted on the electrochromic device coupled with daylighting controls [2]. Other researchers demonstrated a similar control strategy using external venetian blinds and a dimmable electric lighting system in a test cell and a full-scale occupied building [3]. There are no comprehensive field-monitored performance data that quantifies the energy benefits of both systems working interactively.

In this study, we present results from a full-scale testbed demonstration that was conducted over the course of a year in two side-by-side, fully furnished but unoccupied test rooms located in a federal office building. The entire scope of work included further refinements to a dynamic venetian blind/lighting system, energy measurements, and human factors tests. These tests differed from earlier reduced-scale field tests in that the system design was iteratively tuned to solve and accommodate full-scale, observable issues such as venetian blind behavior, motor noise, and occupant preferences. The rooms were fully instrumented to collect data on cooling load, lighting energy consumption, system operation, and environmental quality. The energy results are documented here. Performance of the dynamic envelope/lighting control system is documented in [4]. Results of the human factors tests are given in [5].

2. Background

This research is part of a larger multi-phase research and development program whose primary objective was to develop *integrated* building envelope, daylighting, and lighting systems. The large variation in solar radiation due to diurnal and seasonal changes of sun and sky conditions is a major cause of both high energy use and peak demand, and of occupant discomfort. However, there is an optimum cooling and lighting energy balance between the envelope and lighting system that can be used to advantage to reduce this large variation: daylight can be used to offset lighting energy use and the heat gains associated with the electric lighting system, but the admission of too much daylight introduces solar heat gains that can increase cooling loads associated with the window system. By taking an integrated systems approach to combining disparate components, greater energy savings can be attained with improved occupant comfort over conventional design practice.

Simulation results from early studies revealed the potential of this concept. In California, our energy simulation models predicted that 500-800 MW of peak electricity demand can be saved with this integrated approach over business-as-usual practice for new construction and partial retrofit of office buildings alone by the year 2005 [6]. Since lighting and cooling in commercial buildings constitute the largest portion of peak electrical demand, promotion of such integrated systems can also become a cost-effective option for owners and utilities.

DOE-2 building energy simulations were used initially to model actively controlled venetian blinds with daylighting controls, "manually" operated shading systems (activated every hour when glare or direct sun was detected), and advanced electrochromic glazings [7]. Total annual energy savings of 16-26% were attained with the venetian blind/lighting system compared to an unshaded low-E spectrally selective window with daylighting controls in Los Angeles, California. The energy impact of predictive control algorithms was also investigated in detail.

Field tests using the dual chamber calorimeter Mobile Window Thermal Test (MoWiTT) facility indicated that the automated venetian blind/lighting system with a less than optimal control algorithm was still more than twice as effective at reducing peak solar gains under clear sky conditions as a static unshaded bronze glazing with the same daylighting controls, while providing the same level of useful daylight [8]. A separate year long test was also conducted in a 1:3 reduced-scale test cell to determine the lighting energy savings potential of the automated venetian blind/lighting system and to further develop the control algorithm and hardware solution under real sky conditions [9]. Lighting energy savings of 37-75% were attained with the dynamic system compared to a partially closed, static blind with the same lighting control system for south to southwest-facing windows on clear sunny days.

In terms of evaluating comfort and environmental quality, a RADIANCE visualization simulation study was conducted to evaluate visual comfort associated with a dynamic electrochromic glazing [10]. The dynamic window was able to control the window, interior task, and remote surface luminance levels to within recommended practice standards over the course of a clear, sunny day in Phoenix, Arizona. The clear and tinted static glazings were not.

The full-scale testbed facility completed the development process of the prototype system by enabling us to test and evaluate the design in full-scale. New energy-efficient technologies must be well tested and proven before they are introduced to the building industry, to ensure performance and to reduce real and perceived risk. Through limited tests in actual buildings, performance data can be provided to industry, utility program managers, or design professionals who need data to assess the aesthetics, cost, and energy performance of the technology. This testbed demonstration was both an R&D facility to help answer research questions and a limited proof-of-concept test, allowing practical "bugs" to be worked out of an innovative building system.

3. Method

3.1. Facility Description

The full-scale Oakland Federal Building testbed demonstration facility was designed to measure the electric lighting power consumption and the cooling load produced by the window and lighting system under realistic weather conditions. The facility consisted of two side-by-side rooms that were furnished with nearly identical building materials and furniture to imitate a commercial office-like environment (Figures 1, 2, and 3). Each test room was 3.71 m wide by 4.57 m deep by 2.68 m high (12.17 x 15 x 8.81 ft). The southeast-facing windows in each room were simultaneously exposed to approximately the same interior and exterior environment so that measurements between the two rooms could be compared.

Because this facility was installed in an existing commercial office building and in a built-up urban area, a limited number of external conditions was measured. A datalogging station located on the roof of a five-story adjacent building wing monitored global and diffuse horizontal exterior illuminance, horizontal global solar radiation, and outdoor dry-bulb temperature (shielded from solar radiation). Interior measurements included horizontal workplane illuminance, vertical illuminance, power consumption of all plug loads and mechanical equipment, cooling load, interior air temperatures, and other information pertaining to the status of the dynamic window and lighting system.

Identical automated venetian blind/lighting systems were installed in each room so that the position of the prototype and base case systems could be interchanged. Both test rooms were located in the southeast corner of a larger unconditioned, unfinished space (213 m^2, 2300 ft^2) on the fifth floor of a 18 story tower. Room A was located to the east of Room B and was subject to slightly more early morning shading from an adjacent east building wing. The building was located at latitude 37˚4' N, longitude 122˚1' W. The testbed windows faced 62.6˚ east of true south. Both windows' view were obstructed by five to eight-story buildings one city block away and by several 24-story buildings three to six city blocks away (Figure 4). These obstructions did not cause direct solar shading of the test rooms after 7:45 from the spring to autumnal equinox.

3.2. Window Condition

The existing window system consisted of 6 mm (0.25 in) single-pane, green-tinted glass (PPG Solex, Tv=0.75, SHGC=0.46, U-Value=6.24 W/m^2-˚K) with a custom aluminum frame. The window opening was 3.71 m (12.17 ft) wide and 2.74 m (9 ft) high with five divided lights ranging in width from 0.61-0.67 m (2.02-2.19 ft). The visible glass area was 7.5 m^2 (80.8 ft^2). The window-to-exterior-wall-area-ratio was 0.65. The window was recessed 0.43 m (1.4 ft) from the face of the building and had 0.13 m (5 in)-deep interior and 0.03 m (1 in) deep exterior mullions.

A 0.127 m (0.5 in)-wide, curved slat, semi-specular white aluminum venetian blind was fitted in a white painted wood frame and placed 0.127 m (0.5 in) away from the interior face of the existing glazing system. The blind covered the entire vertical height of the window and was not retractable, only the angle of the slats could be altered. A small direct current motor drive at the base of the window blind was used to alter blind angle in synchronization with the lighting controls via National Instruments LabView computer control.

3.3. Lighting Condition

Two pendant indirect-direct (~95%, 5%) fixtures with four T8 32W lamps, continuous dimmable electronic ballasts, and a shielded photosensor were used in each room (Figure 5). The two fixtures were placed along the centerline of the window with the first fixture spaced 0.61 m (2 ft) from the window wall and the second spaced 0.86 m (2.82 ft) apart. The photosensor was placed at one end of the second light fixture and flush with the bottom of the fixture, 2.08 m (6.8 ft) from the window wall. The ballasts were rated to produce 10% light output for a minimum power input of 33%. The lighting power density was 14.53 W/m^2 (1.35 W/ft^2).

3.4. Base Case System

For the base case system, the venetian blind was set to one of three fixed, static positions throughout the day to simulate "manual" operation: 45˚ (nearly closed), 15˚ (partly closed), or 0˚ (horizontal), where a positive blind angle is defined from the horizontal plane with the slats inclined downwards for a ground view from the interior. For the base case with no daylighting controls, the electric lights were set to full power throughout the day. For the base case with daylighting controls, the lighting system was designed to supplement daylight, if available, to provide an average design illuminance of 510 lx at the horizontal workplane area located 2.44-3.35 m (8-11 ft) from the window wall and 0.74 m (2.42 ft) on either side of the centerline of the test room.[2] If there was sufficient daylight to displace all electric lighting, the lights were shut off after a 10 min delay. The lighting control system was installed and commissioned with a prototype ballast controller so that there was a proportional response to available daylight every 30 s.

3.5. Prototype System

For the prototype dynamic system, the venetian blinds were activated every 30 s to block direct sun and maintain the daylight design illuminance of 540-700 lx at the average workplane area, if daylight was available. If there was no direct sun present and daylight illuminance levels were within design parameters, the blinds were set to maximize view (horizontal). The range of motion for the blind was restricted to 0-68˚ to limit sky view glare, where at 60˚ the slats are just touching and at 68˚ the slats are squeezed shut to the mechanical limit of the venetian blind system. Diffuse daylight was still admitted at 68˚. The daylighting control system was the same described for the base case system.

3.6. Experimental Procedure

Data were collected for 14 months from June 1, 1996 to August 31, 1997. The prototype system was developed iteratively over the year to refine control system algorithms and hardware operations according to observations in the field. Additional system parametrics were performed to address particular issues raised by the human factors study or to characterize and improve system performance. Although these system parametrics were monitored, data in this study are presented for the same prototype control system throughout the year.

3.7. Data Sampling and Recording

For energy and load monitoring, data were sampled every 6 s then averaged and recorded every 6 min from 6:00-19:00 and every 20 min from 19:00-6:00 (standard time) by Campbell Scientific CR10 dataloggers. Weather data, collected on a nearby roof, were sampled and recorded every 1 min by a CR10 datalogger.

3.7.1. Lighting Power

Electric lighting power consumption was measured in each test room with watt transducers (Ohio Semitronics GW5) that were accurate to 0.2% of reading. The daily lighting energy use was defined as the sum of 6 min data over a 12 h period defined by 6:00-18:00. To determine the comparability of data between the two rooms, the same

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[2] The average workplane illuminance at this location will hereafter simply be referred to as the"average workplane illuminance".

venetian blind and lighting configuration was set in both rooms then the resulting daily lighting energy use was compared periodically throughout the year.

Daily lighting energy use of Room A was found to correlate to within -6 or -19 Wh (1%, n=2) of Room B when both rooms had the same fixed blind position, and to within -12±46 Wh (2.6±5.4%, n=25) when both rooms were operating with the dynamic system. Room A was subject to slightly lower solar exposure than Room B for the same window and lighting configuration due to its position relative to the exterior surroundings. A comparison of the two rooms revealed that during some hours, the daylight illuminance in Room A was a maximum of ~10% lower than Room B. However, these differences in average daylight illuminance levels at the workplane did not necessarily correlate to differences in lighting energy use between the two rooms, since the reading at the photosensor determined lighting power consumption.

3.7.2. Cooling Load

Cooling load measurements result from a net heat balance on each well-insulated test room, where the interior air temperature was maintained at a constant level (±1˚C) by an electric resistance heater and a building chilled water liquid-to-air heat exchanger. Flow rate and inlet and outlet temperatures were measured. Individual three-speed fan coil units (McQuay TSH-081F) with modified electronic controls (to modulate the fixed speed settings) and two-stage electric duct heaters (Delta Flo DH) were placed in the plenum of each test room to deliver air at adequate temperature and volume to meet the load. A linear slot diffuser (Titus ML-39) was located near the window, the return was located in the back of the room. Building chilled water was delivered the cooling coils in each test room through a controlled circuit using a 2 cm (0.75 in) two-way control valve and valve actuator (Honeywell ML7984). The chilled water flow rate was maintained within 0.048-0.189 m^3/s (0.75-3.0 gpm). A booster chilled water pump (Grundfos UP26-96F) was used to maintain differential pressure. Control of the fan coil unit was based on a return air temperature sensor located in the plenum above the return air grille. Stand-alone PID controllers (TCS/Basys Controls SD1000) with separate heating and cooling outputs were used for room temperature control. The cooling output was used to control the two-way proportioning valve. Heating output was controlled with zero-crossing triac (low noise) power controllers.

High stability thermistors (YSI 46016, <0.01˚C drift at 70˚C for 100 months) were individually calibrated and placed in thermowells in the supply and return chilled water line. A turbine flowmeter (Hoffer 3/8", linear flow range 0.75-7.5 gpm) was placed in the filtered supply chilled water line and calibrated against a reference flowmeter periodically. Thermistors (YSI 44018, ±0.15˚C) were placed in the plenum, return air grille, and supply air grille to monitor plenum and room air temperature. The mechanical system was designed to allow the measurement of cooling loads to within ±3% of reading and electric power consumption (Ohio Semitronics watt transducers, GW5) from the fans, receptacles, and heating coils to within ±1% of reading.

The test rooms were constructed to minimize heat transfer out of and into each room in order to isolate the measured cooling load to that imposed only by the window and electric lighting system. The walls and plenum ceiling were well insulated (R19, 0.3 W/m^2-K). The metal studs were insulated to prevent thermal bridging. Carpeting (1.3 cm, 0.5 in), plywood (1.3 cm), and rigid insulation (R12, 0.47 W/m^2-K) were applied over the existing concrete decking floor. All penetrations through the walls and ceiling were caulked and sealed, and weatherstripping was applied to the door. Within the plenum, ducts and chilled water lines were insulated (R12, 0.47 W/m^2-K) from the point of penetration to the fan coil unit. Since the window head height extended 1.37 m (4.5 ft) above the finished acoustical tile ceiling, a highly reflective window film (3M P18-AR, SHGC=0.23) was applied to the glazing in the plenum then insulated with R19 batt insulation applied to the interior face of the glazing.

The cooling load contribution of the window and electric lighting system was calculated for each 6 min interval by summing the measured cooling load (based on measured flow rate and inlet and outlet temperatures) and the heating and fan energy use (assuming 100% conversion to heat). The daily cooling load was determined by the sum of this 6 min data over a 12 h period defined by 6:00-18:00. Because of the inherent complexity introduced by the central plant mechanical system, no conversions were made from cooling load to energy use. The average hourly cooling load was determined for each room by the average of 6 min data over the hour. The peak cooling load and hour were defined by the test room with the higher average hourly cooling load over the 12 h period. Several filters were applied to the data. If the room air temperature of Room A or B was found to be outside of the range defined by 21.1±1.0˚C (69-71˚F) for more than 10% of the 12 h period, the day's data were discarded. If the time stamps between the two room datalogging systems were found to have drifted by more than 3 min, the data were also discarded.

Nighttime mechanical system calibration tests and tests conducted with the mechanical system off were used to ascertain the comparability between the two rooms given instrumental error, differences in construction, the rooms' relative position to the exterior and interior environment, and the mechanical systems' operation. Additional daytime tests were conducted periodically throughout the year with the same venetian blind and lighting configuration set in both rooms to determine test room comparability.

The daily cooling load of Room A was found to correlate to within 87±507 Wh (0.5±5.0%, n=33) of Room B when both rooms had the same fixed or dynamic blind position and the cooling load exceeded 5 kWh, and to within 534±475 Wh (15±12%, n=13) when cooling load exceeded 1.5 kWh but was less than 5 kWh. Less accuracy of the turbine flowmeters at low flow rates was the source of the larger error at the lower cooling loads. Loads less than 1.5 kWh, typical of overcast cool weather conditions, were not analyzed. Loads between 1.5 to 5 kWh are presented with the proviso that there is more error associated with these data.

Oscillations between the heating and cooling system with a period of 8-12 min were found to occur on occasion when the system was transitioning between heating or cooling modes in order to maintain the defined air temperature deadband of ±1˚C within each test room. With 6-min data collection, the peak load was estimated by averaging over the hour interval. As such, peak loads (>0) of Room A were found to correlate to within -24±114 W (-0.6±6.4%, n=23) of Room B when both rooms had the same fixed blind position and to within 5±68 W (0.4±6.0%, n=31) when both rooms were operating with the dynamic envelope/lighting system.

4. Results

We present below comparative data for the base case static venetian blind defined with and without daylighting controls, because daylighting controls are presently used in only a small percentage of U.S. buildings. Daily lighting energy, daily cooling load, and peak cooling load data are given for the entire year in Figures 6-8. Tables 1-3 give the average daily cooling load and lighting energy reductions for the daylit case by season, where seasons were defined by the days falling within 1.5 months of the day of the equinox or solstice.

4.1. Base case with daylighting controls

If both the base case and prototype have the *same* daylighting control system, then daily lighting energy savings and cooling load reductions resulting from the dynamic blind were roughly proportional to the degree of the static blind's openness and its relation to solar position. To clarify, we show how the dynamic system saves energy compared to both the 0˚ and 45˚ static blind with the same daylighting controls on typical clear days (Figures 9-10, August 15 and 18, 1996).

On August 15, the dynamic system achieved substantial reductions in cooling load (21%) and peak cooling load (13%) and good reductions in lighting energy use (21%) compared to the static 0˚ system. Cooling load reductions were the result of the dynamic system's control over solar heat gains. Lighting energy reductions were due to the illuminance control strategy of the dynamic system. Note how the dynamic venetian blind closed at 7:00 then started to open at 11:00 to maintain a constant daylight illuminance at the workplane as daylight availability changed. After 14:30, the dynamic blind moved to the horizontal position to maximize view and daylight admission. With the dynamic venetian blind, average illuminance levels at the back of the room were well controlled in the morning hours to within 500 to 1000 lx (the blinds were closed to the mechanical limit when illuminance exceeded the 700 lx design level), while the static 0˚ system resulted in illuminance levels of 1000 to 2500 lx. Visual and thermal comfort may be compromised with the static system.

On August 18, the dynamic system achieved significant lighting energy reductions (46%) but small reductions in cooling load (4%) and peak cooling load (8%) compared to the static 45˚ blind. The partly closed blind was able to control solar gains as well as the dynamic blind. However, the static system could not meet the design workplane illuminance with daylight. Fluorescent lights were turned on at 12:10, approximately 2.5 hours earlier than the dynamic system. On both days, spikes in the venetian blind angle, seen in the figures, were due to hysteresis or oscillations in the venetian blind motorized control system; this problem was solved in later tests.

In general, lighting energy savings were achieved through the optimal response of the dynamic venetian blind to changing exterior daylight levels, primarily in the mid-afternoon when the sun was out of the plane of the window and when exterior daylight illuminance levels were diminishing. The prototype blind was able to maintain a higher level of illuminance for a longer period than the partly closed blind. Overcast and partly cloudy conditions resulted in less lighting energy savings; e.g., the daily lighting energy use of the prototype blind on October 24, a heavily overcast day, was 2046 Wh/day with savings of only 14% compared to the 45˚ blind.

Cooling load reductions were achieved principally by the control of direct transmitted solar heat gains and to a lesser degree, by reduced heat gains from the electric lights. The more closed the static base case blind system with respect to direct solar radiation, the lesser the savings achieved by the prototype system: average daily cooling reductions of 6-15% (45˚ static blind) and 17-32% (0˚ static blind) were achieved across seasons by the dynamic blind compared to the static blind.

On clear sunny days, peak lighting demand was the same in both cases since the design illuminance setpoint was exceeded during the peak period, causing the lights to shut off. Peak cooling loads occurred in the early to mid-morning hours when the sun was in the plane of the window and again reflects largely the difference in direct transmitted solar heat gains resulting from the average hourly blind position (Figure 8 and Table 3). Average peak cooling load reductions of 118-200 W or 6-15% (45˚ tilt angle) and 379-562 W or 18-32% (0˚ tilt angle) were achieved across seasons by the dynamic blind compared to the static blind. This hourly average load reduction is a measure of both the instantaneous load reduction and the benefit from active control derived from the previous 1-2 hours given lightweight, steel-frame construction.

4.2. Base case with no daylighting controls

Compared to the base case static blind (at any angle) with no daylighting controls, daily lighting energy savings of 623-2376 Wh/day (22-86%) were obtained with the prototype dynamic system (Figure 6, noted on graph as "no daylighting"), where the daily lighting energy use of the base case was 2800 Wh/day. The degree of savings was proportional to daylight availability. On clear sunny days, daylight displaced lighting energy use completely for ~50% of the daylight hours. On overcast days, electric lighting was required to supplement daylight for a much larger percentage of the day.

Peak lighting demand reductions were optimal during peak cooling periods—for periods of high daylight availability and peak cooling, the prototype system shut the lights off, thus realizing a savings of 100% or 256-270 W compared to the non-daylit base case.

Cooling load data were not collected for the non-daylit base case on a routine basis. However, measurements made on three clear days in late July 1996 show that average daily cooling load reductions of 4772±677 Wh (28±5%) were obtained by the prototype system compared to the static horizontal blind, where the average daily cooling load of the base case was 17,311±3645 Wh (Figure 7). Average peak cooling load reductions of 803±192 W (28±6%) were attained for these same conditions.

These energy and load reductions were achieved with a) the use of a properly commissioned, prototype continuous dimmable lighting control system with a 30 s response to available light, b) the optimal operation of the automatic venetian blind which provided sufficient daylight when available, and c) the electric lights being turned off after a 10 min delay if there was sufficient daylight to provide the design workplane illuminance level.

5. Discussion

5.1. Daily lighting energy

The venetian blind is an optically-complex shading device that transmits, reflects, and scatters direct sun, diffuse skylight and reflected light from the ground and surrounding obstructions. The resulting illuminance distribution within a room is therefore a complex function of solar conditions and the venetian blind angle. The lighting control system adds a second layer of complexity since the spatial distribution of daylight produces a variable photosensor response, which is then processed to control the dimming of the electric lights. With static homogeneous window systems (i.e., transparent glazing without shading devices), the relationship between lighting energy use, glazing condition, and daylight availability has been theoretically characterized [11]. With increased glazing visible transmittance or window area, simulated annual lighting energy use decreases asymptotically to a minimum level (defined by nighttime and minimum lighting power usage) where "daylight saturation" is attained.

Despite the optical complexity of the venetian blind and its effect on the lighting control system, a similar relationship was exhibited with these monitored data between the daily lighting energy use and increased daylight aperture—which in this context is defined by the degree of blind openness. This finding substantiates the arguments made in the Results section. If we constrain the upper daily lighting energy use at full power within the 12 h day to 2800 Wh (parameters a+b below), the fit between average daily global horizontal illuminance, $x=E_{vgh}$, to daily lighting energy use (=y) for various blind angles was fairly good (r^2=0.51-0.94) with the following non-linear regression:

$$y=a+be^{(-cx)} \tag{1}$$

Equations, data and error analysis are given in Table 4 and Figure 11. The minimum lighting energy use, or the "a" parameter, can theoretically equal zero during periods or at building locations with high daylight availability because the lighting control system has been designed with a shut-off option.

The near closed static blind data exhibited a more shallow curve than the dynamic blind curve, illustrating its decreased daylighting efficiency with increased daylight availability compared to the dynamic system. The dynamic blind performance was found to be comparable to the most open static blind (0˚), and arguably better than the 15˚ and 45˚ partly closed blinds for the full range of exterior illuminance levels throughout the year. Whereas approximately the same daily lighting energy use can be achieved with the static horizontal blind, the dynamic blind substantially reduces the cooling load while providing control of direct sun and interior illuminance levels for improved thermal and visual comfort.

Daylight "availability" can be distinguished by the presence of daylight (9.6 h in winter, 12+ h in the summer) and by weather conditions (clear, overcast). If energy data are binned by month or length of day, we find that the minimum lighting energy use, or parameter "a", decreases with increased length of day (Figure 12)—assuming the same non-linear relationship. Most daily lighting energy use can theoretically be displaced if for the summer period defined by March through September (a=280 Wh), whereas no more than ~80% of the daily lighting energy use (a=587 Wh) can theoretically be displaced during the winter period defined by September through March. Rough extrapolations can be made to determine potential lighting energy savings for various climates and building orientations in a similarly sited and configured building space by using monthly climatic data.

5.2. Daily Cooling Load

Heat gains from the window predominate the monitored daily cooling load and thus reflects the radiative, conductive, and convective exchange between the optically-complex venetian blind window system and the interior environment. Other research [12] and intuition supports the generalization that a closed blind that blocks and reflects direct transmitted solar radiation provides more solar control than a more open blind. Indirect reflected and absorbed solar radiation from the ground and sky contributes a much smaller fraction to the total cooling load. The conductive and convective contributions to the heat gain within a space are nominally the same with varying blind angle for an interior blind.[3] Assuming that the differences in electric lighting heat gains are small compared to the solar heat gains, lower cooling loads will be attained in the test room where the blind was "more closed" for a larger percentage of the day.

These trends were reflected in the monitored daily cooling loads. Smaller cooling load reductions were attained by the dynamic system when compared with the partly closed 45˚ static blind, while larger reductions were attained compared to the open, horizontal static blind, shown in Figure 13 as a function of total daily global horizontal radiation (summed over the 12 h period). All data are shown with daylighting controls. The scatter in data may be primarily attributed to the large differences in outdoor air temperature over the course of the year (12-36˚C).

Because the dynamic system was designed to always block direct sun, the cooling load throughout the year was rendered fairly insensitive to changes in solar radiation levels. We note this behavior in a plot of the dynamic system's daily cooling load as a function of total daily global solar radiation, binned by average daily outdoor dry-bulb temperature (Figure 14). Note for the same 6˚C temperature bin, the cooling load was roughly the same (±1-2 kW) across a solar radiation range of 3500-7500 W/m^2-day. For these data, the scatter may be attributed to differences in outdoor wind speed or to differences in daylight availability and the subsequent difference in electric lighting heat gains. Given insufficient monitored data to show a similar trend, we can only surmise that the data for the static systems indicate that cooling loads increase with increased solar radiation within similar temperature bins, with the rate of increase greater for the more open blind.

5.3. Optimal Balance

While the vertical scales are not directly comparable, note in Figures 6 and 7 how lighting energy use with the static blind system decreases, while cooling load increases with increased blind openness; e.g., the least closed horizontal static blind resulted in the least lighting energy use of the three static positions, but was penalized with higher cooling loads for the same day.

Note also how lighting energy use decreases with increased daylight availability while inversely, cooling load increases with increased solar radiation. The prototype system achieves the least increase in both lighting energy use and cooling load with increased daylight availability, denoting its superior ability to optimize the daily balance between both daylighting and solar heat gains.

6. Conclusions

A dynamic venetian blind and dimmable electric lighting system was designed to optimize daylight admission and solar heat gain rejection in real-time, while accommodating additional occupant considerations. A full-scale testbed facility consisting

3 Air flow at the exterior (wind) and interior (due to mechanical cooling) are roughly the same. Convective coupling that occurs within the air layer between the glazing and the blind (spaced 0.127 m away from the glazing) is of minor consequence since the heat gain is already within the room interior.

of two side-by-side, southeast-facing private offices was used to determine the energy savings potential of this system compared to a static venetian blind system with and without dimmable daylighting controls in the moderate climate of Oakland, California. Cooling loads due to the window and electric lighting system and lighting energy use were monitored every 6 min throughout the day, as well as other control and performance parameters such as interior illuminance levels and status of the dynamic blind. With these data, we were able to make the following conclusions:

1. Conservatively, average daily cooling load reductions of 7-15% (45˚ blind angle) and 17-32% (0˚ blind angle) were achieved across seasons by the dynamic system over a static venetian blind with the same dimmable lighting control system. Average daily lighting energy reductions of 19-52% (45˚ blind angle) and -14 to +11%% (0˚ blind angle) were achieved across seasons as well. Cooling data generally reflect sunnier, warmer weather[4] since we discarded the monitored day if the daily cooling load was less than 1.5 kWh. Lighting energy reductions are reported for monitored data taken over the course of a year.

2. With no daylighting controls, daily lighting energy savings of 22-86% (any static blind angle) were obtained for overcast to clear sky conditions throughout the year, while average daily cooling load reductions of 28±5% (0˚ blind angle) were obtained on clear days in July. We would argue that these savings are more indicative of the technology's potential benefit since dimmable daylighting controls are used in a very small percentage of new and existing U.S. commercial buildings. Stepped, dual level manual switching is the minimum requirement imposed by most state energy codes. If dimming controls are used, experience has shown that these systems are rarely well commissioned and operating at their full potential. Experience has also shown that manually controlled shading devices are not effectively used. Occupants tend to alter the position of the blind only when severe uncomfortable conditions occur. Often, the occupant is not present in the room.

3. Peak cooling load reductions of 18-32% were attained by the dynamic system compared to a static, horizontal blind with daylighting controls and 6-15% compared to a 45˚ static blind. If no daylighting controls were used, then 28% reductions were attained compared to a static horizontal blind on clear days in July. Normally, the mechanical engineer must assume that the shading devices and electric lights will be at worst case conditions when sizing the mechanical system, and as such, will oversize the system accordingly. These peak reductions will not only reduce expensive demand operating charges, but may also enable the owner to capture first time cost reductions by downsizing the mechanical system capacity in new construction. In a broader view, the reduction in peak load may deter the future growth of utility generation facilities.

4. The variability in savings reported above are due to an assumed static venetian blind position. If the static venetian blind was more closed to exclude direct solar radiation, then the reported cooling load reductions were at the lower end, while the lighting energy savings were at the higher end of percentage savings. If the static venetian blind was horizontal for increased view, then the daily cooling load reductions were higher, while the lighting energy savings were lower. This balance between optimum cooling load control and daylight admission was achieved consistently by the dynamic system over the full

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[4] Acceptable days typically had an average horizontal global radiation levels of~3500-7500 W/m^2-day and an average dry-bulb outdoor temperature of 12-36˚C.

range of solar conditions throughout the year. The static systems could not achieve this balance.

5. The above energy savings provided by the automated venetian blind/lighting system were given relative to three static blind angles with or without the same daylighting control system in an office with high transmission glazing and large glazing area. For lower transmission glazing or for smaller glazing areas, one could expect these savings to decrease slightly. For manual operation with fully retracted blinds, lighting savings could be further decreased, but cooling loads would increase. Savings should also be less if the window was shaded by exterior obstructions (overhangs or fins), especially for orientations that are subject to direct sun (i.e., south, east, west). These southeast facing windows already had a significant portion of the sky view obstructed by nearby buildings, being located in a built-up metropolitan area, so energy savings would be greater with a more open site. In addition, cooling load reductions would be less if dual-pane spectrally selective glazing was used instead of a tinted monolithic configuration. Substantial reductions in cooling load with approximately the same lighting energy savings may be obtained for between-pane or external dynamic venetian blind systems. Commercially-available, automatically controlled interior shading systems are used in Europe and in some U.S. commercial buildings to control direct sun. These shading systems are not designed or operated to control interior illuminance levels nor are they operated in synchronization with the daylighting control system, and so will not attain the energy savings delineated here.

6. This dynamic system has the advantage of always blocking direct sun, of providing view when there is no direct sun in the plane of the window (maximum view was possible for 50% or more of the day throughout the year), and of providing controlled illuminance levels throughout the day. This control of the variability in solar and daylight conditions that occur at the perimeter zone may reduce the thermal and visual discomfort associated with this zone, particularly for occupancies with high computer use.

7. The system was designed from commercially-available, off-the-shelf components to meet near-term research goals. Minor modifications were made to the venetian blind and lighting control system to enable the two systems to interact, but the added cost for these system modifications was low. Additional tests were conducted to build in control flexibility. Human factors tests were also conducted to evaluate improvements to the environment and acceptability of the design.

For those researchers involved in the solar-optical design of more advanced glazing technologies, these field test data may provide a real world check against data obtained in a laboratory setting alone. While the motorized venetian blind solution may be objectionable to those wary of mechanical failure, the prototype solid state electrochromic glazings provide a more elegant long-term solution. Concerns posed by material scientists working on the development of electrochromics may be addressed by drawing analogies to this research.

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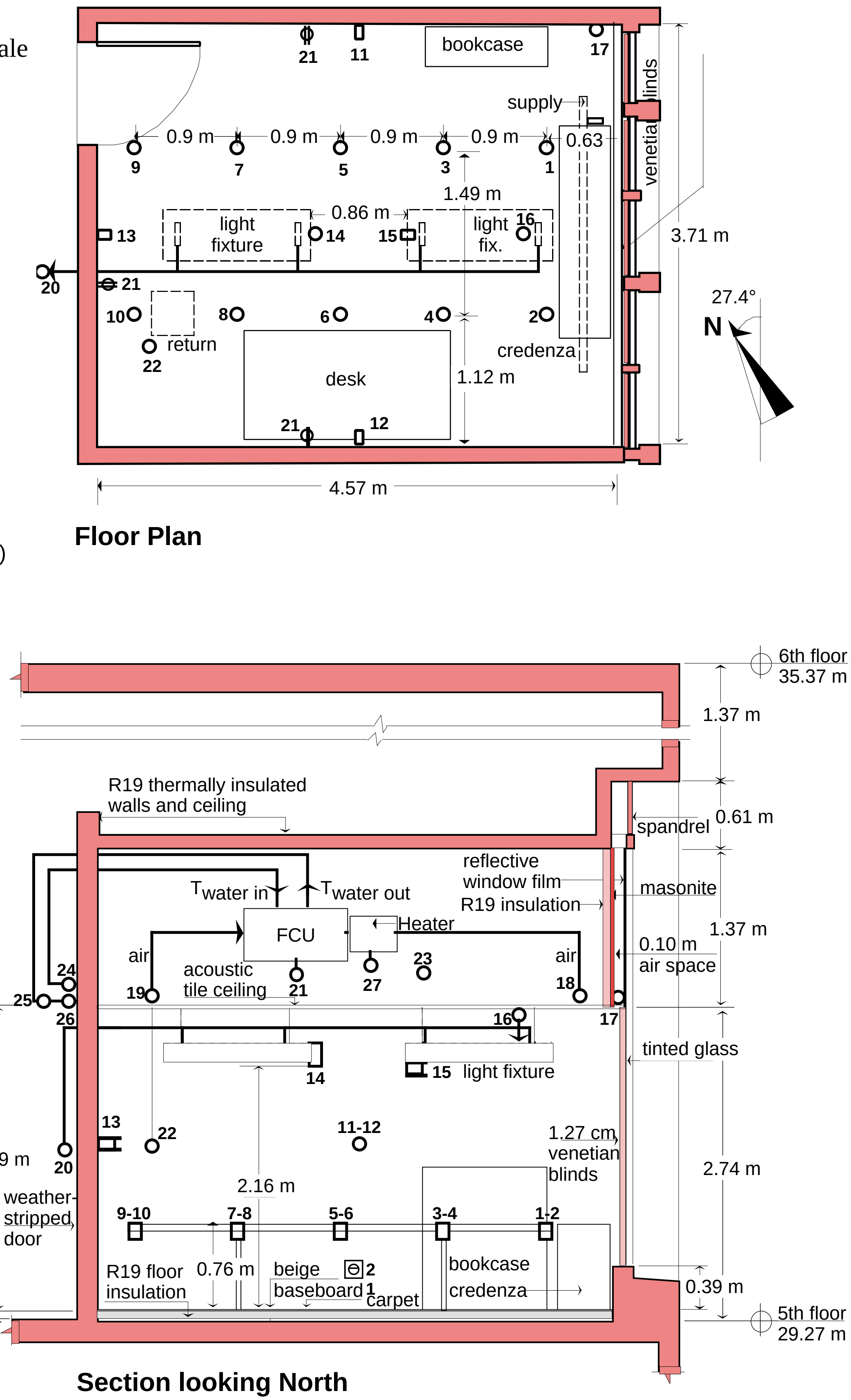
Fig. 1. Floor plan and section view of full-scale test room.

Monitored data:

1-10 Evg horizontal (lux)
11-12 Evg vertical (lux)
13 Evg window-shielded (lux)
14 Photosensor signal (V)
15 Evg window-(shielded) (lux),
16 Evg ceiling (lux)
17 Photosensor at plenum (V)
18 Tair supply (°C)
19 Tair return (°C)
20 Lighting power (W)
21 Fan power (W)
22 Tair room (°C)
23 Tplenum (°C)
24 Twater in (°C)
25 Twater out (°C)
26 Flow (gpm)
27 Heater power (W)



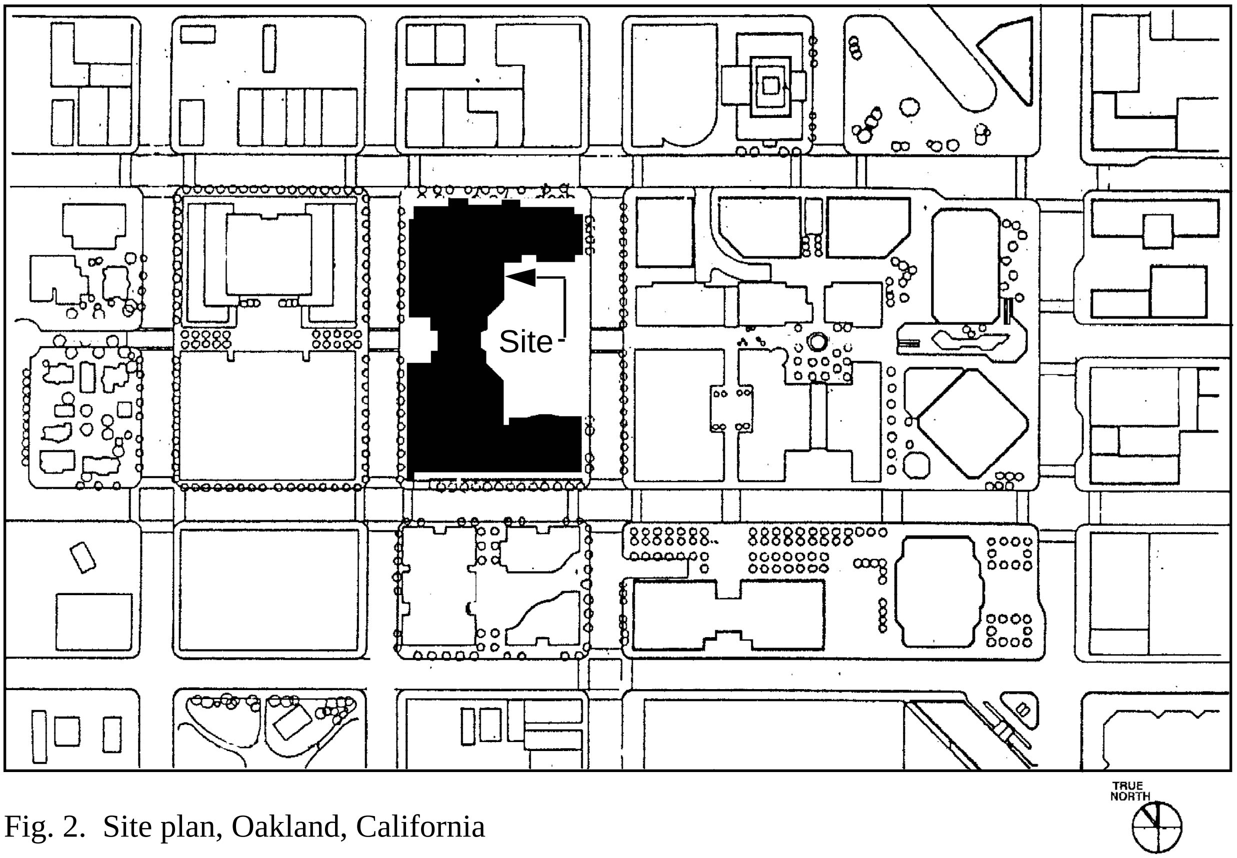


Fig. 2. Site plan, Oakland, California

Fig. 3. Interior view of testbed.

Fig. 4. View of surroundings outside the testbed window.

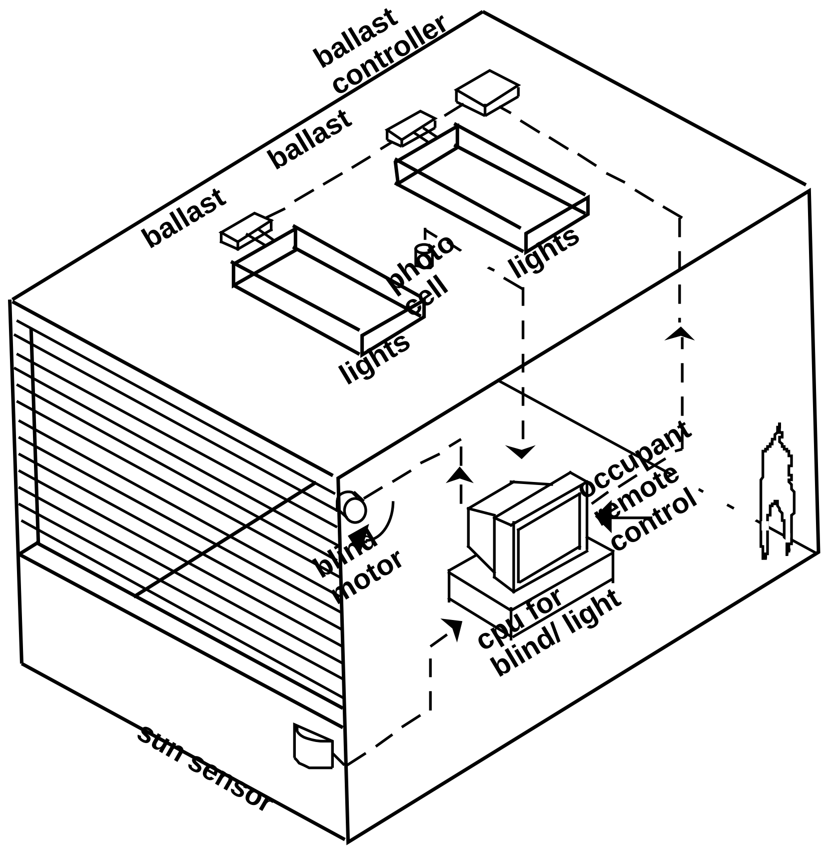


Fig. 5. Schematic of automated venetian blind/lighting system.

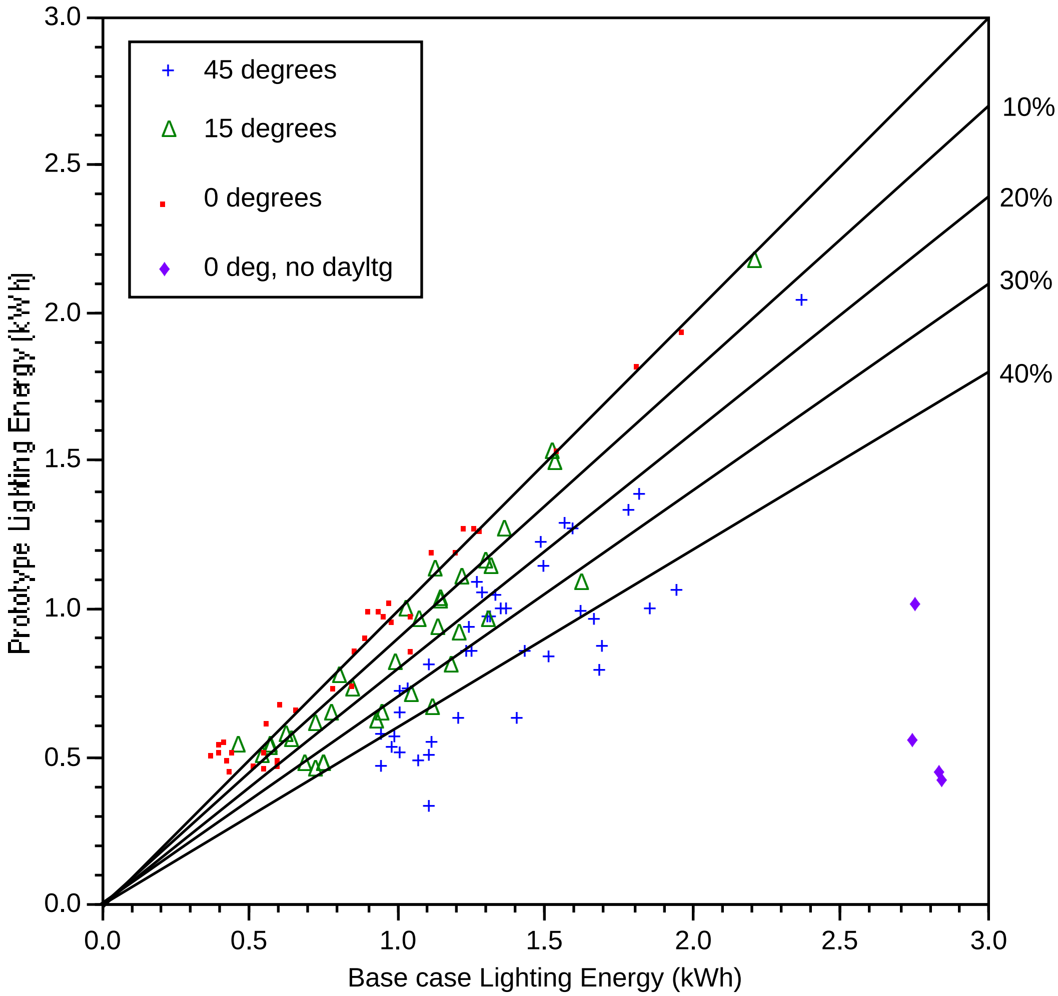


Fig. 6. Daily lighting load (kWh) of the base case and prototype venetian blind/ lighting systems, where the base case was defined by three static blind angles, 0˚ (horizontal), 15˚, and 45˚. Diagonal lines on the graph show percentage differences between the base case and prototype. Both cases were defined by the prototype continuous dimming lighting control system or, within a limited set of tests, the lighting control systems with no dimming controls ("no dayltg"). Lighting power density is 14.53 W/m^2 (1.35 W/ft^2), glazing area is 7.5 m^2 (80.8 ft^2), and floor area is 16.96 m^2 (182.55 ft^2). Data collected from June 1996 to August 1997. Measurement error between test rooms is 12±46 Wh (2.6±5.4%).

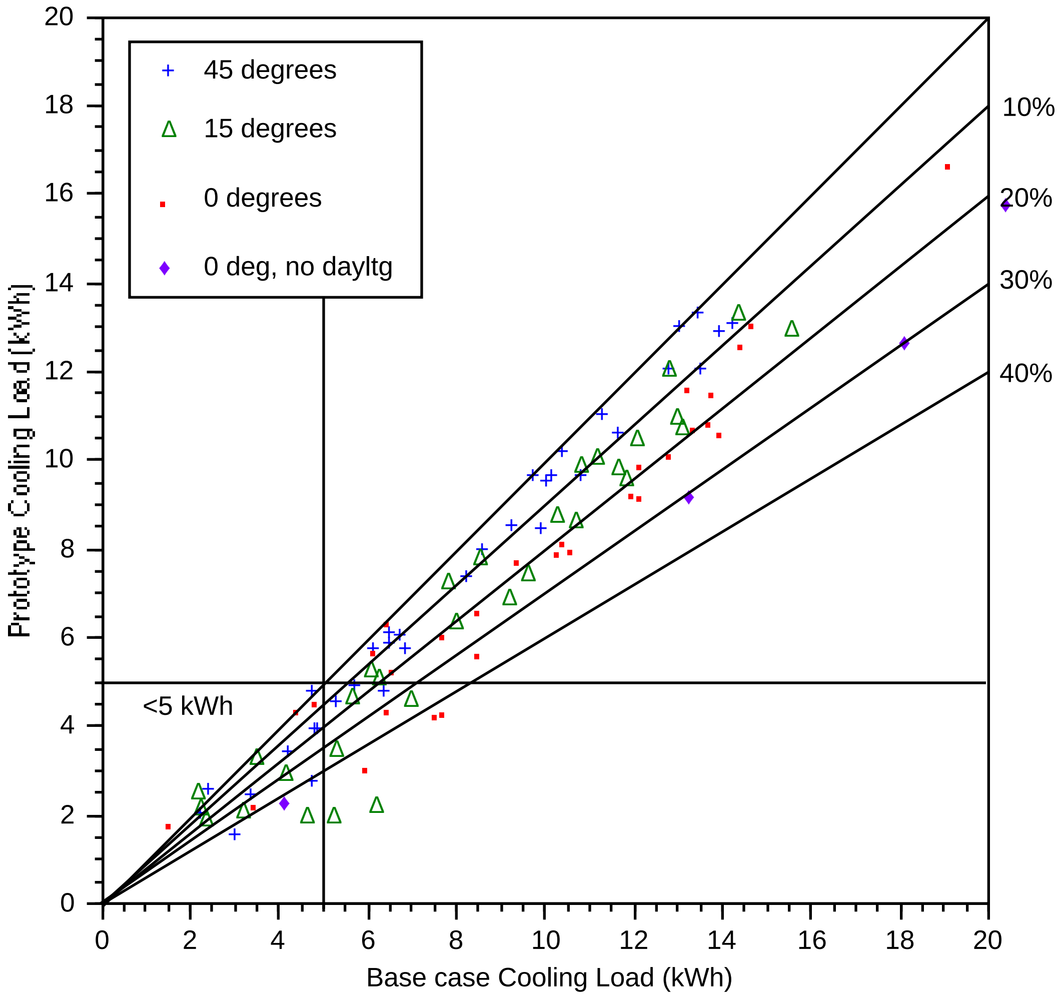


Fig. 7. Daily cooling load (kWh) of the base case and prototype venetian blind/ lighting systems, where the base case was defined by three static blind angles, 0˚ (horizontal), 15˚, and 45˚. Measurement error between rooms for loads greater than 5 kWh was 87±507 Wh (0.5±5%), and for loads within 1.5-5 kWh was 534±475 Wh (15±12%). Diagonal lines on the graph show percentage differences between the base case and prototype. Both cases were defined by the prototype continuous dimming lighting control system or, within a limited set of tests, with no dimming controls (“no dayltg”). Lighting power density is 14.53 W/m^2 (1.35 W/ft^2), glazing area is 7.5 m^2 (80.8 ft^2), and floor area is 16.96 m^2 (182.55 ft^2). Data collected from June 1996 to August 1997.

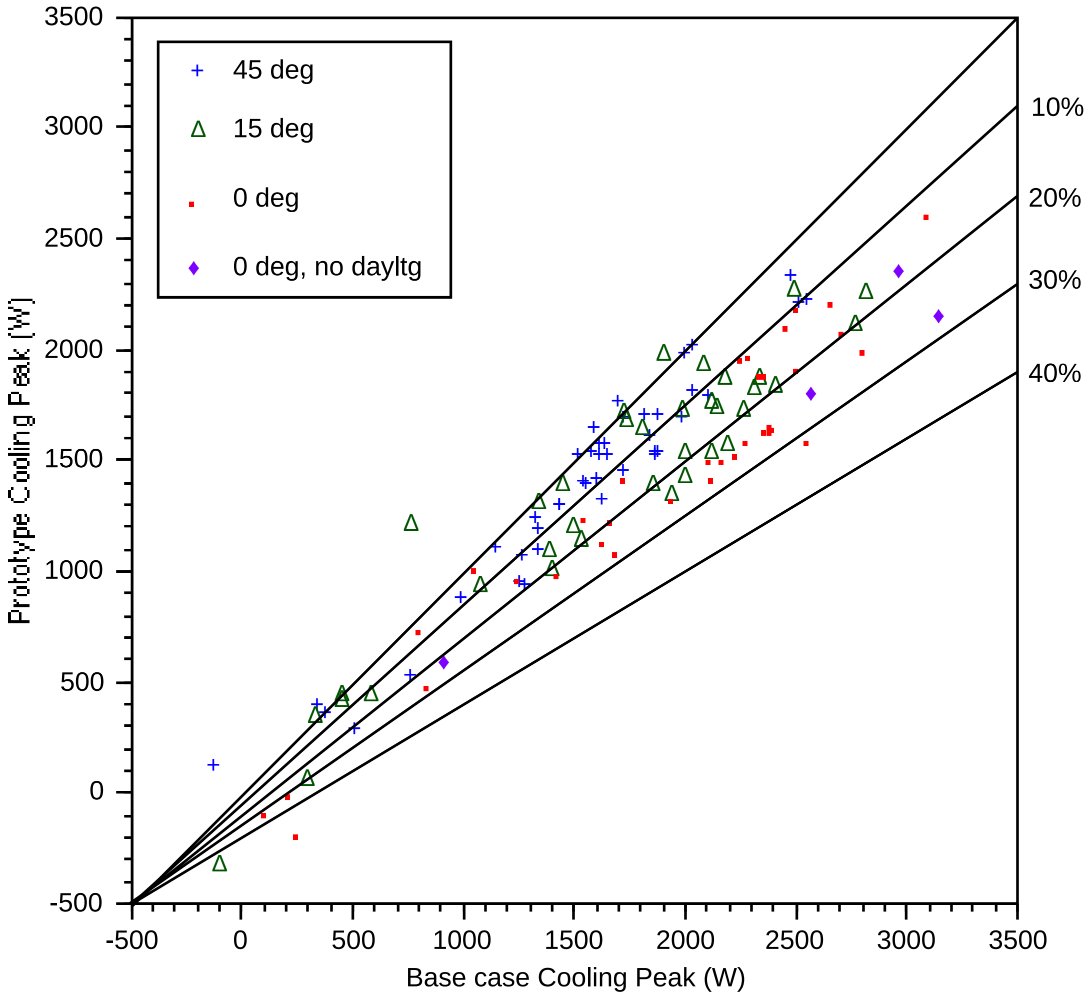


Fig. 8. Peak cooling load (W) of the base case and prototype venetian blind/ lighting systems, where the base case was defined by three static blind angles, 0°, 15°, and 45°. Measurement error between roomw was -24±114 W (-0.6±6.4%). Diagonal lines on the graph show percentage differences between the base case and prototype. Both cases were defined with the prototype continuous dimming lighting control system, or within a limited set of tests, with no dimming controls ("no dayltg"). Data collected from June 1996 to August 1997.

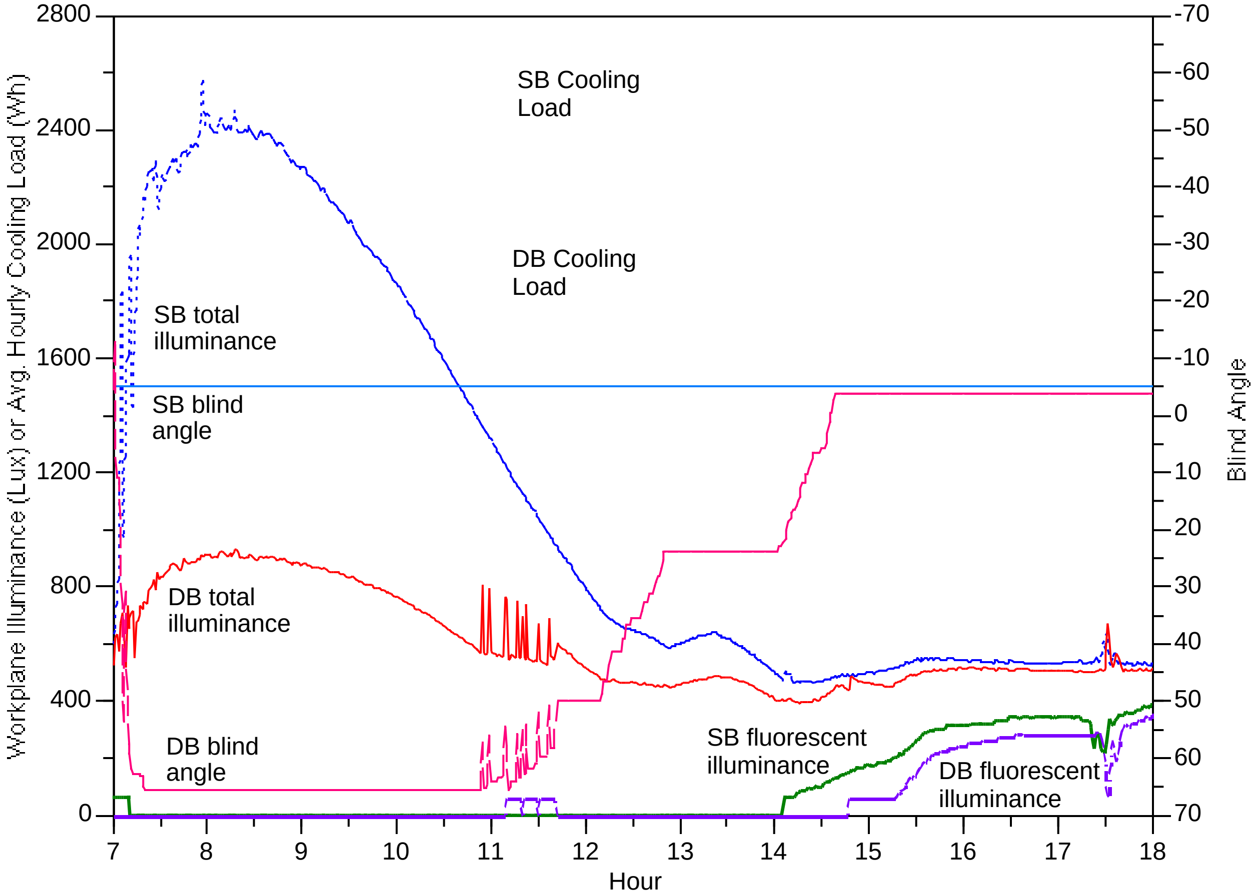


Fig. 9. Monitored total workplane illuminance, fluorescent lighting illuminance, and blind angle for the static horizontal blind (SB) and the dynamic venetian blind (DB), both with daylighting controls. Daily cooling load savings were 2917 W (21%). Peak cooling load reductions were 332W (13%). Daily lighting energy savings were 127 Wh (21%). Data are shown for southeast-facing offices in Oakland, California on a clear day, August 15, 1996.

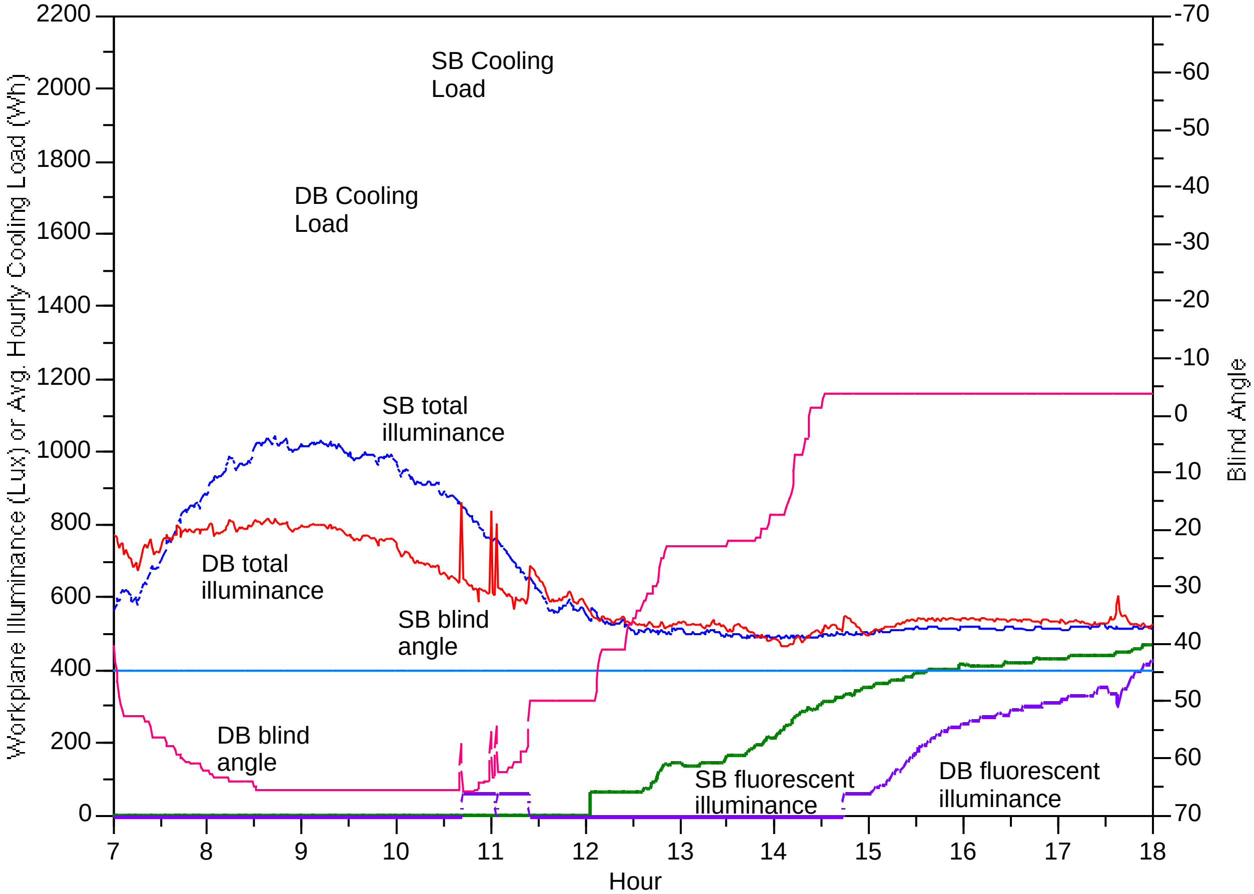


Fig. 10. Monitored total workplane illuminance, fluorescent lighting illuminance, and blind angle for the static 45° blind (SB) and the dynamic venetian blind (DB), both with daylighting controls. Daily cooling load reductions were 448 W (4%). Peak cooling load reductions were 157 W (8%). Daily lighting energy savings were 452 Wh (46%). Data are shown for southeast-facing offices in Oakland, California on a clear day, August 18, 1996.

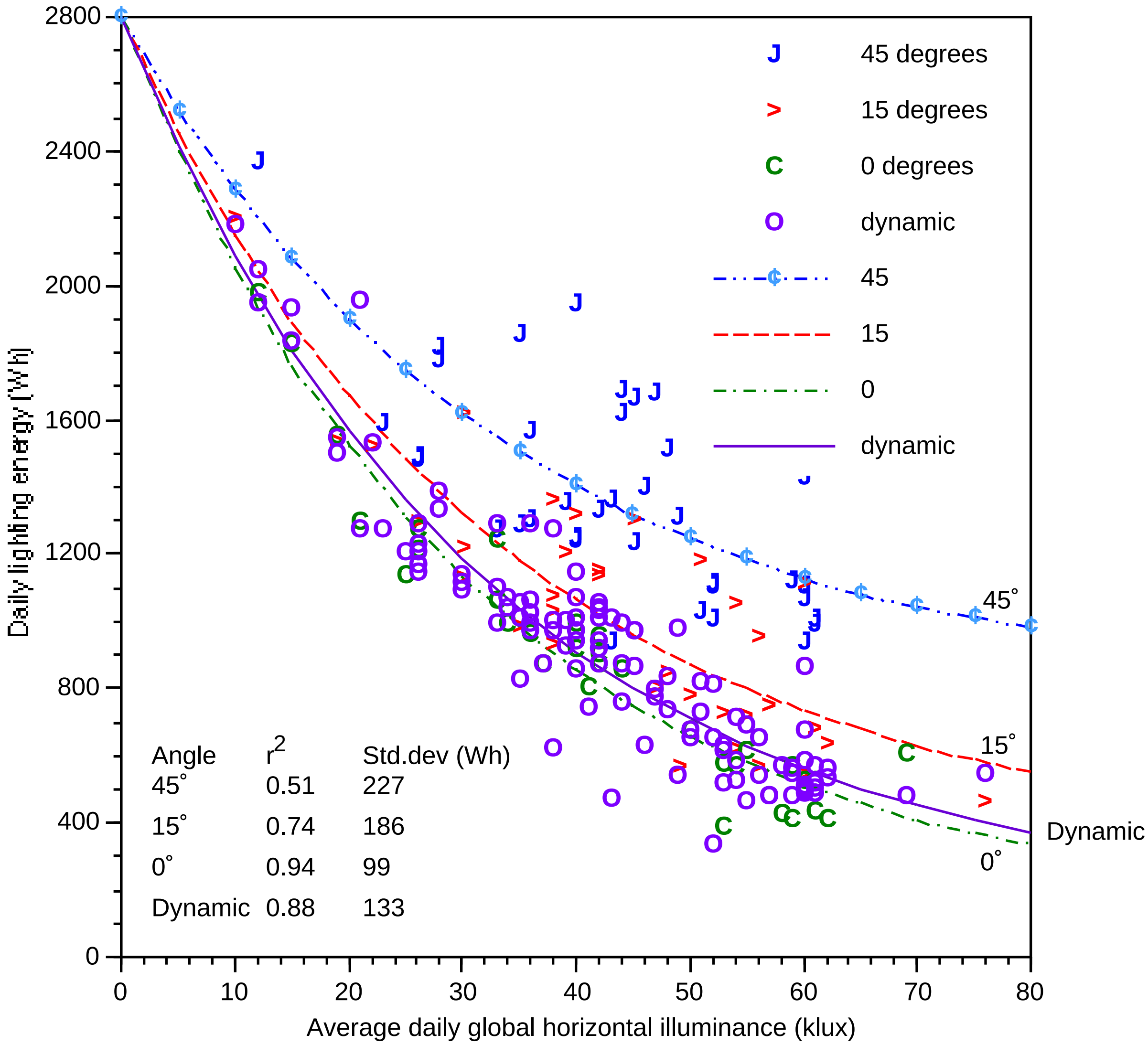


Fig. 11. Daily lighting energy use (Wh) as a function of average daily global horizontal illuminance (klux) for four static blind positions and the dynamic prototype. The non-linear correlation fits are shown as continuous lines. All cases were defined with the prototype continuous dimming lighting control system. Data are shown for the monitored period of June 1, 1996 to August 31, 1997.

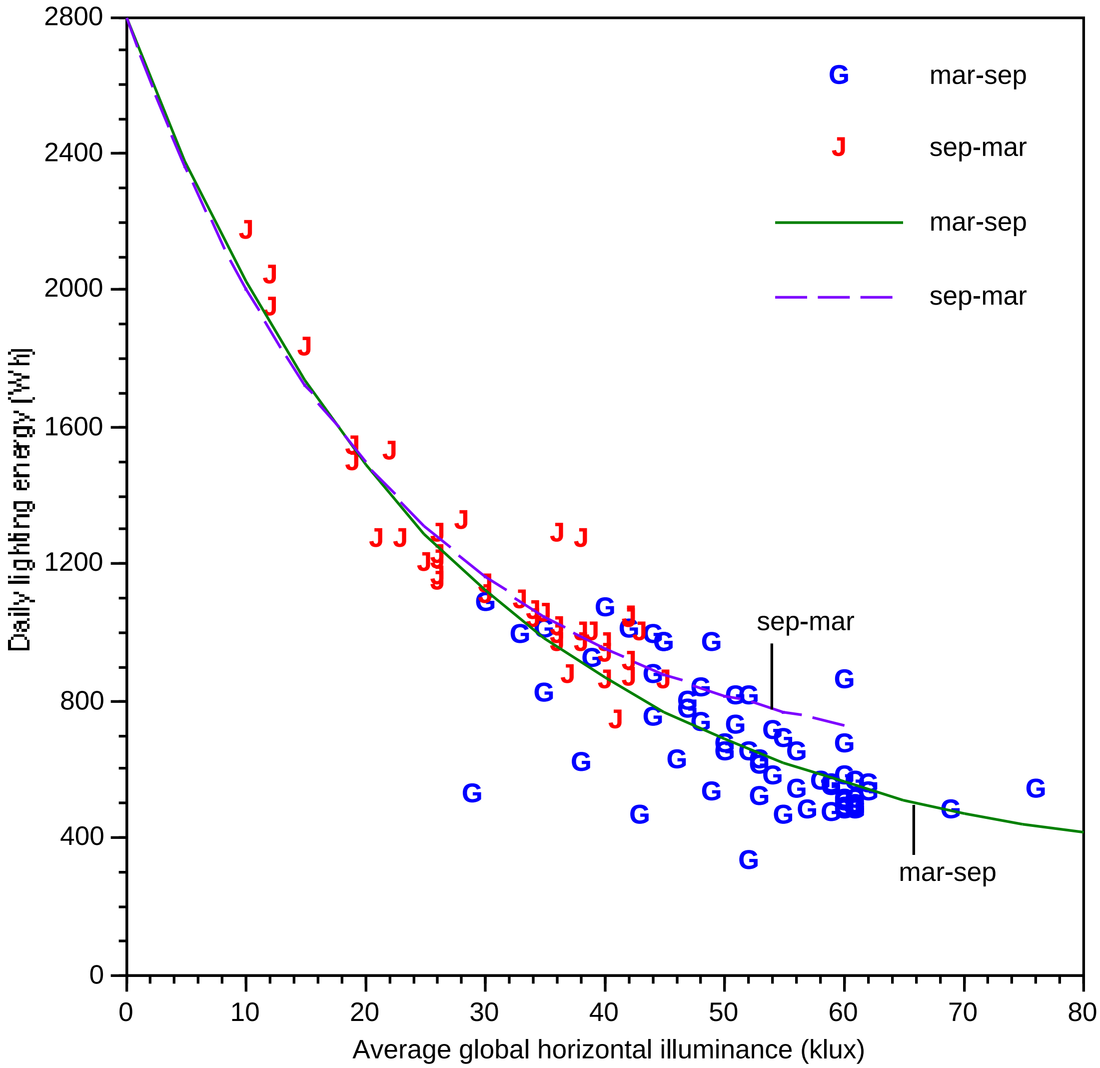


Fig. 12. Daily lighting energy use (Wh) of the dynamic prototype binned by season as a function of average daily global horizontal illuminance (klux). The fits are grouped by March 21 through September 20 data (high daylight availability) and September 21 through March 20 data (low daylight availability).

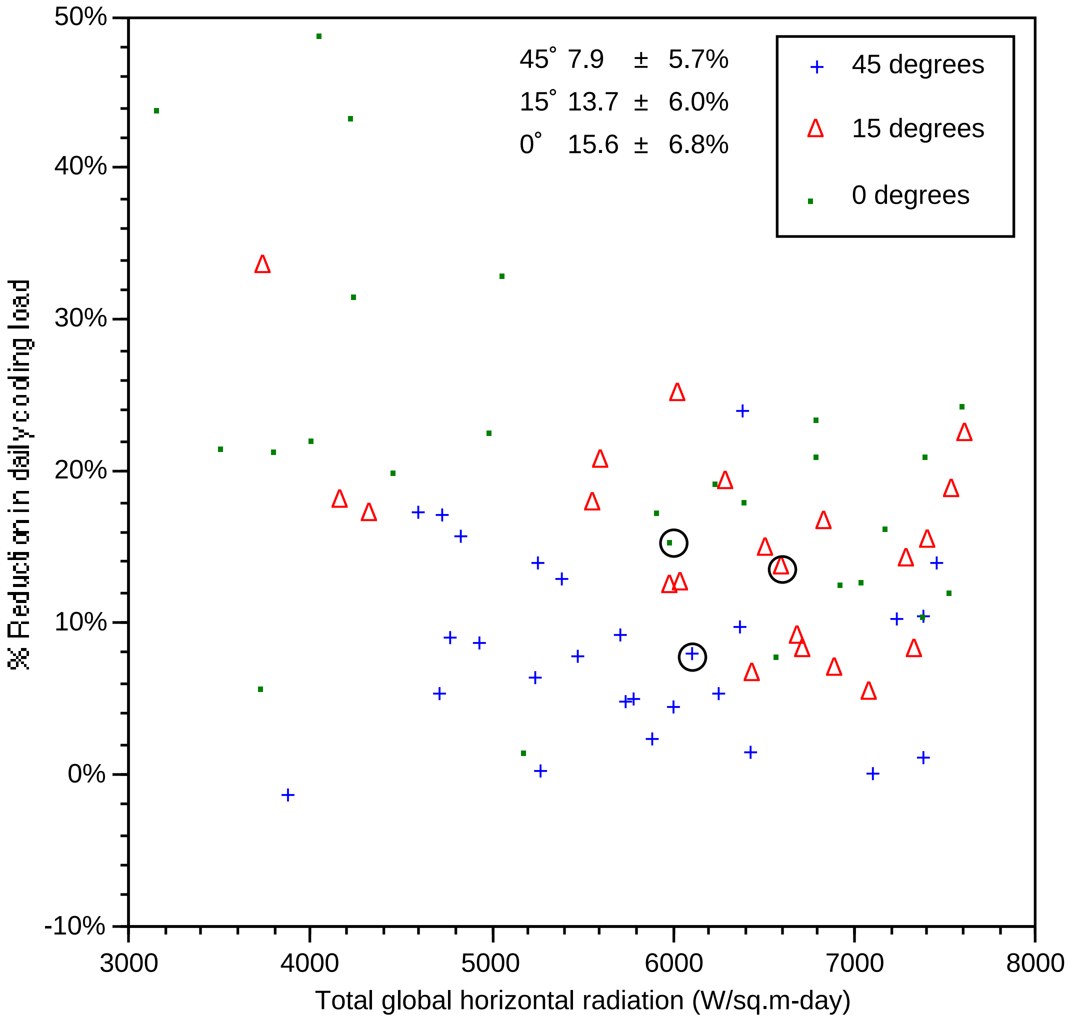


Fig. 13. Percent reduction in daily cooling load compared to the base case static venetian blind with the same dimmable prototype lighting control system as a function of total daily global horizontal radiation (W/m^2-day). All daily cooling loads greater than 5 kWh. Average values shown circled on graph.

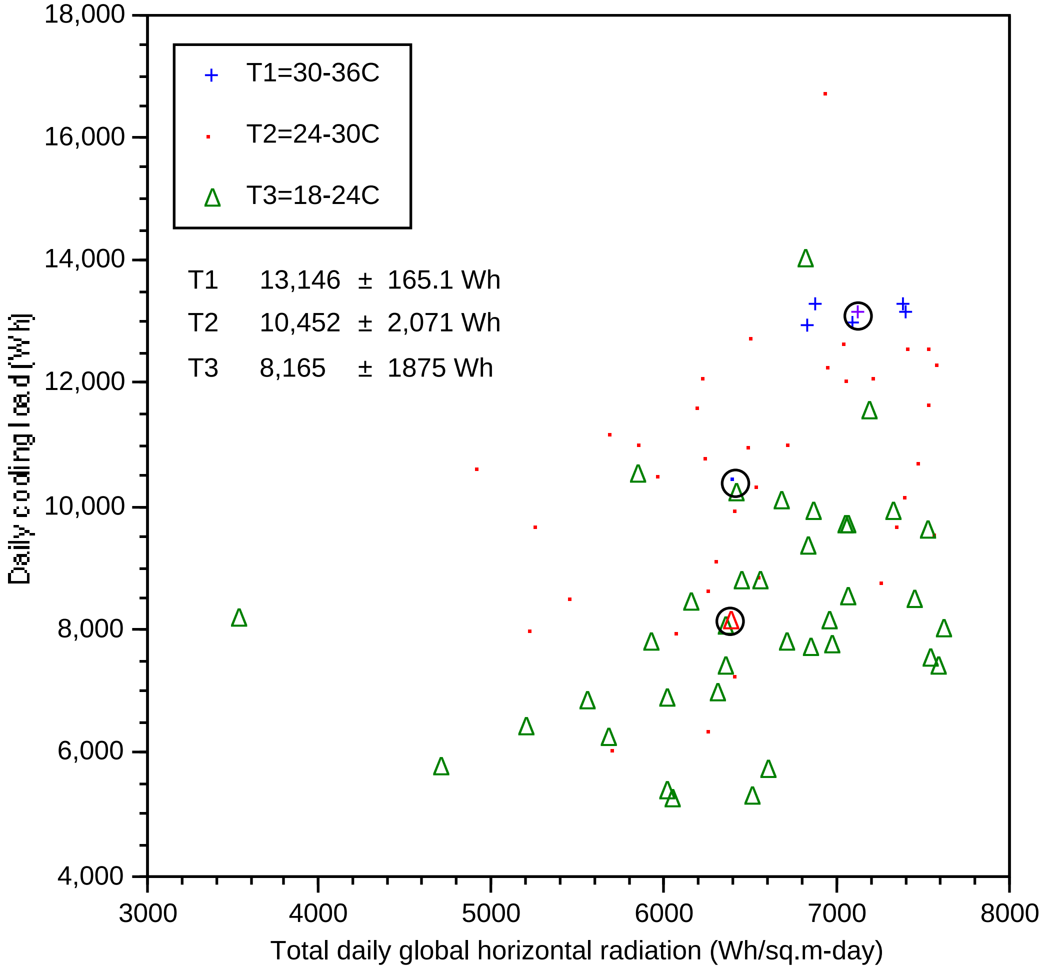


Fig. 14. Daily cooling load (Wh) binned by solar radiation and average daily outdoor dry-bulb temperature as a function of total global horizontal solar radiation (W/m^2) for the dynamic venetian blind/lighting system. Temperature bins are T1=30-36˚, T2=24-30˚, T3=18-24˚. All cooling loads are greater than 5 kW. Average values shown circled on graph.